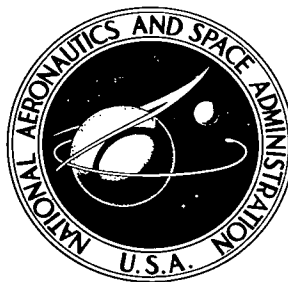


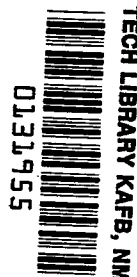
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# FOULING CHARACTERISTICS OF ASTM JET A FUEL WHEN HEATED TO 700° F IN A SIMULATED HEAT EXCHANGER TUBE

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## ABSTRACT

Supersonic aircraft might profitably utilize the greater heat sink that would be made available if fuels could be heated to higher temperatures than is current practice. Therefore, three ASTM Jet A fuels were heated to 700<sup>0</sup> F (644 K) under simulated heat exchanger conditions. Tests were made with air-saturated and deoxygenated fuels at pressures ranging from 2.5 to 615 psia ( $1.72 \times 10^4$  to  $424 \times 10^4$  N/m<sup>2</sup> abs) for periods of 20 hours, and the amounts of tube surface fouling were determined. Very small amounts of solids collected on the surface in all cases; the accumulated solids represented from 0.05 to 2.5 ppm of the fuel. The deposits decreased markedly when the dissolved oxygen was removed from the fuel and, in general, decreased with increasing pressure.

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## SUMMARY

Operating economies may be realized in supersonic aircraft if the heat sink of the fuel can be utilized to cool the engines and the airframe. Tests were performed to determine if there were combinations of conditions whereby ASTM Jet A fuel could be heated to 700° F (644 K) without heat exchanger performance loss due to fuel deposits. In these tests an air-to-fuel heat exchanger was simulated by a 5/32-inch- (0.397-cm-) diameter Nichrome V tube 54 inches (1.37 m) long, heated electrically (9000 Btu/(hr)(ft<sup>2</sup>) or 2840 W/m<sup>2</sup>). Flow rate, pressure, and fuel outlet temperature were held constant for 20 hours or until 60 pounds (27.3 kg) of fuel had passed through the tube.

The oxygen content of the fuel was established at either 0.3 or 45 parts per million (minimum and air-saturated conditions). Test pressures ranged from 2.5 to 615 psia ( $1.72 \times 10^4$  to  $424 \times 10^4$  N/m<sup>2</sup> abs). The three batches of fuel used were all within ASTM specification limits for Jet A fuel but were further classified as "good", "poor", and "poorest" from a thermal stability standpoint.

Deposit accumulation was determined by cutting the tube into 1- or 2-inch (2.54- or 5.08-cm) lengths and analyzing the carbon in each length by a combustion technique. Deposits tended to form local accumulations or peaks rather than uniform coatings. The poorer two fuels formed deposits at two local areas when oxygen saturated. With minimum oxygen, the peak associated with a lower wall temperature disappeared. Total deposit accumulation was always significantly lower for tests with minimum oxygen.

Increasing fuel pressure from atmospheric to 315 psia ( $217 \times 10^4$  N/m<sup>2</sup> abs) caused total and local deposit accumulations to decrease and peaks to occur at higher temperatures. No improvement was indicated above 315 psia ( $217 \times 10^4$  N/m<sup>2</sup> abs).

The deposit measuring technique presented herein should prove of value in future fuel fouling research. It also suggests a method for cleaning fuel heat exchangers.

## INTRODUCTION

Almost all engine cycles require some cooling. A convenient sink for this heat is the fuel. When kerosene-type fuels are heated, small amounts of solids may form. These solids can foul heat exchanger surfaces, clog filters and fuel injectors, and cause controls to stick. The thermal instability problems associated with these fuels are probably due to the presence of very small amounts of nonhydrocarbon impurities in the fuel. Pure hydrocarbons are not degraded at fuel temperatures in current aircraft.

Fuels for commercial and military subsonic operations are stable to at least 300° F (422 K). The commercial fuels (Jet A, Jet A-1, and Jet B) must pass a 300° F (422 K) preheater outlet test (ASTM specification D-1655-63T), and the military fuels JP-4 and JP-5 must pass the same test per Military Specification J-5624F. The fuels are aerated (air-saturated) before the thermal stability tests are performed.

The Coordinating Research Council, under Federal Aviation Agency contract, studied the fuel thermal stability problems of a Mach 3.0 supersonic transport (SST) (refs. 1 and 2). Partly as a result of these studies the heat load to the fuel was reduced. The flight speed was reduced to Mach 2.7 and the maximum temperature of the jet fuel kept below 350° F (450 K) to assure satisfactory operation of the aircraft.

Fuels are exposed to higher temperatures in advanced military aircraft. The Air Force has specified JP-6 for this use, and it must pass a preheater outlet temperature test of at least 425° F (491 K) without excessive fouling (Military Specification J-25656B). This fuel is refined to reduce impurities, and as a consequence it is more expensive than the commercial grades. Fuel cost is an important consideration in commercial aircraft especially in a supersonic transport where fuel costs are now expected to be about one-half of total operating costs.

Increasing the heat sink capacity of commercial fuel would provide additional ways to increase engine efficiency and reduce specific fuel consumption. More efficient engine cycles can use greater cooling, especially when the turbine inlet temperature exceeds material limits, thereby requiring cooling of hot end components, such as the turbine, using compressor bleed air. For supersonic or subsonic aircraft with high compressor pressure ratios, the compressor bleed air becomes so hot that air requirements for cooling may become excessive. Additional fuel heat sink capacity to reduce cooling air temperature and flow requirements would be beneficial.

Several approaches have been considered to increase the heat sink capacity of the fuel. These schemes have ranged from precooling kerosene-type fuels to the use of cryogenic fuels, such as liquid hydrogen or liquified natural gas (ref. 3). Although these schemes have merit, there are strong logistic and economic arguments for further

utilization of the heat sink capacity of commercial fuel if means of avoiding the thermal stability problems can be found.

The currently available heat sink capacity for Jet A fuel is about 120 Btu per pound ( $280 \times 10^3$  J/kg) when the fuel is heated from  $75^\circ$  to  $300^\circ$  F (297 to 422 K). If the fuel were heated to  $700^\circ$  F (644 K), the heat absorbed would increase to 400 to 475 Btu per pound ( $930 \times 10^3$  to  $1110 \times 10^3$  J/kg) depending on the amount of vaporization. The amount of vaporization is dependent on the fuel system pressure. However, the fact remains that from three to four times more heat sink capacity is available at  $700^\circ$  F (644 K) than at  $300^\circ$  F (422 K).

During studies and literature surveys it was determined that there was potential for increasing the useful heat sink capacity of commercial fuel. There were several indications in the literature that deoxygenated fuel had a reduced tendency for fouling (e.g., refs. 4 and 5). Methods of minimizing oxygen content while handling large quantities of fuel were demonstrated during the B-70 program (ref. 6). The potential for reaching significantly higher temperatures with kerosene fuels, at least for short periods of time, has been indicated in references 7 and 8. There was also a strong interest at Lewis as to whether pressure has an effect on fuel fouling.

The influence of two variables, oxygen content and fuel pressure level, were investigated in the experiments conducted at the Lewis Research Center and reported herein. A series of tests was performed using resistance-heated Nichrome V tubes to simulate fuel passages of an aircraft heat exchanger. The fuels were heated from  $70^\circ$  to  $700^\circ$  F (294 to 644 K). The wall- to fuel-temperature difference ranged from  $100^\circ$  to  $300^\circ$  F (56 to 168 K). Tests were run on three batches of fuel which meet ASTM Jet A specifications. Pressures during the various tests ranged from 2.5 to 615 psia ( $1.72 \times 10^4$  to  $424 \times 10^4$  N/m<sup>2</sup> abs). The flow was laminar near the entrance with Reynolds number near 100. The exit Reynolds number ranged to 25 000 depending upon the fluid pressure. Fuels were tested in both the air-saturated and the deoxygenated state. After testing, the deposits along the length of the tubes were determined by a combustion technique. The effects of these deposits on heat exchanger performance and overhaul times are discussed.

## APPARATUS AND PROCEDURE

### Fuels

Inspection information on the three batches of fuel tested is listed in table I. Two drums of the fuel designated as LeRC 67-1 were obtained directly from a pipeline to the Cleveland Hopkins Airport. This fuel had high thermal stability, as shown in table I. Four drums of the fuel designated as LeRC 67-2 were taken at one time from a 25 000-gallon (94.6-m<sup>3</sup>) tank at Lewis. As the tank is periodically refilled but seldom emptied,

TABLE I. - FUEL PROPERTIES

Property	Fuel		
	LeRC 67-1	LeRC 67-2	RAF 178-64
Gravity, °API	43.1	44.4	43.0
Distillation, °F (K):			
Initial boiling point	359 (454)	334 (440)	364 (457)
10 percent	388 (470)	365 (458)	384 (468)
50 percent	428 (493)	402 (478)	424 (490)
90 percent	480 (522)	463 (512)	478 (520)
End point	517 (542)	510 (538)	513 (540)
Flash point, °F (K)	142 (334)	120 (322)	146 (336)
Sulfur, wt. %	0.022	0.034	0.204
Aromatics, vol. %	19.4	14.8	19
Thermal stability:			
Maximum tube rating at preheater/filter temper- ature in °F (K):			
275/375 (408/463)	-----	-----	<sup>a</sup> Code 2
300/400 (422/477)	-----	-----	<sup>a</sup> Code 3
325/425 (436/491)	-----	-----	<sup>a</sup> Code 3
350/450 (449/505)	<sup>b</sup> Code 1	-----	-----
400/500 (477/533)	<sup>b</sup> Code 2	-----	-----
425/525 (491/546)	<sup>b</sup> Code 2	-----	-----
450/550 (449/560)	<sup>b</sup> Code 3	-----	-----

<sup>a</sup>With standard ASTM-CRC coker.<sup>b</sup>With modified CRC coker.

this batch might be considered to be typical of a mixture of many shipments. The batch designated as RAF 178-64 was obtained from the Coordinating Research Council fuel bank. It was selected because its thermal stability rating was near the minimum; that is, this fuel represents as poor a fuel as could be expected within specification limits.

## Dissolved Oxygen

The fuels were either air-saturated by bubbling air through them at 1 atmosphere for 30 minutes immediately prior to the test or were deoxygenated by a similar treatment with nitrogen. The oxygen content of the air-saturated fuels was about 45 ppm, while the oxygen content of the nitrogen-purged fuels was less than 0.3 ppm. The pressurizing gases used to displace the air-saturated fuels were mixtures of oxygen and nitrogen prepared to give a 0.21-atmosphere oxygen partial pressure (equivalent to air at 1-

atmosphere pressure) in the supply tank ullage. Nitrogen was the driver gas for deoxygenated fuel tests. A Beckman Model 77700 oxygen analyser was installed after the sixth test and showed that there were no measurable changes in the dissolved oxygen content with changes in system pressure or during the tests.

## Test Conditions

Seventeen tests were run at 3.0 pounds per hour (1.37 kg/hr) for approximately 20 hours or until the total flow was 60 pounds (27.3 kg). One test at 2.5 psia ( $1.72 \times 10^4$  N/m<sup>2</sup> abs) was made at 2.0 pounds per hour (0.91 kg/hr) for 30 hours. Three batches of fuel, five pressure levels, and two oxygen contents were run. However, not all possible combinations of these variables were investigated. The runs and test conditions are listed in table II. The fuel was heated to 700<sup>0</sup> F (644 K) during each test. The average heat flux was around 9000 Btu per hour per square foot (2840 W/m<sup>2</sup>).

## Flow System

Fuels were fed through resistance-heated tubes using a gas-pressurized feed tank and a back-pressurized receiver, as shown in figure 1. Fuel was discharged from the pressurized supply tank through a dip tube and passed through a 0.5-micrometer filter, a flowmeter, a pneumatically operated shutoff valve, and a manually operated throttle valve before reaching the plenum at the entrance to the heated tube. The inlet plenum contained an electrically insulated flange. A direct-current voltage was applied at the inlet of the Nichrome V tube with the exit end grounded. The exit plenum had a settling chamber for particles not adhering to the surface of the heated passage. A sintered metal filter collected all particles escaping the exit plenum. The 700<sup>0</sup> F (644 K) fuel leaving the filter was condensed and cooled to 60<sup>0</sup> F (289 K) before it entered the waste fuel tank.

Nichrome V tubing was used in all tests. Two fuels, LeRC 67-1 and LeRC 67-2, were tested in 5/32-inch- (0.396-cm-) diameter tubing with a 0.020-inch (0.0508-cm) wall. Due to a depletion of tubing stock, a third fuel (RAF 178-64) was run in 3/16- by 0.020-inch (0.476- by 0.0508-cm) tubing. Tube lengths were 54 inches (1.37 m) in all cases except for the one run made at 2.5 psia ( $1.72 \times 10^4$  N/m<sup>2</sup> abs) where a 60-inch (1.524-m) length was used. In this one test, the flow rate was decreased because of exit Mach number limitations. This reduced the Reynolds number and heat-transfer coefficients, and therefore required a longer tube.

An over-temperature controller on the tube wall was set to shut off the power if the wall temperature exceeded a preset value 200<sup>0</sup> F (111 K) higher than that at the start of



TABLE II. - TEST CONDITIONS

[Common conditions: fuel outlet temperature, 700° F (644 K); minimum oxygen content, less than 0.3 ppm; maximum oxygen content,  $\approx 45$  ppm; normal test time of 20 hr at flow rate of  $\approx 3.0$  pounds per hour (9.12 kg/hr). Flow rate was reduced and time increased for run 4 because of exit Mach number limitations.]

Fuel	Run	Pressure		Oxygen content	Tube size <sup>a</sup> , outside diameter, in.
		psia	N/m <sup>2</sup> abs		
LeRC 67-1	1	165	$113.5 \times 10^4$	Maximum	5/32 ↓
	2	165	113.5	Minimum	
	3	20	13.75	Minimum	
	4	2.5	1.72	Minimum	
	5	315	217	Minimum	
	6	315	217	Maximum	
RAF 178-64	7	315	$217 \times 10^4$	Minimum	3/16 ↓
	8	165	113.5	Minimum	
	9	165	113.5	Maximum	
	10	315	217	Maximum	
	11	615	424	Minimum	
	12	615	424	Maximum	
LeRC 67-2	13	615	$424 \times 10^4$	Minimum	5/32 ↓
	14	315	217	Maximum	
	15	165	113.5	Maximum	
	16	165	113.5	Minimum	
	17	315	217	Minimum	
	18	615	424	Maximum	

<sup>a</sup>All tubes had 0.020-in. (0.51-cm) wall.

the run. A time-delay circuit permitted flow to continue for 45 seconds after the power was shut off to cool the tube. A pneumatically operated valve stopped the flow. Also, for safety reasons, the heated tube and its inlet and exit plenums were enclosed in a metal box with a clear plastic cover. The box was lined with electrically insulating material and purged with nitrogen.

## Instrumentation

Most flow rates were measured with a variable-area flowmeter calibrated before and after each run. Accuracy was estimated to be  $\pm 2$  percent. An orifice was used for tests at 615 psia ( $424 \times 10^4$  N/m<sup>2</sup> abs).

Fuel temperatures were measured with iron-constantan (IC) thermocouples in the supply tank, in the oxygen content sensor well, and at the inlet and exit plenums. From five to eight IC thermocouples were also equally spaced along the length of the heated tube. The thermocouple beads were electrically insulated from the tube wall with mica flakes. The insulated thermocouple leads were each wrapped around the tube four times to reduce lead conduction losses. A 150<sup>0</sup> F (340 K) reference junction oven was utilized, and millivolt values were read from a digital voltmeter.

Fuel pressures at the supply tank, inlet and exit plenums, and waste tank were measured with inexpensive Bourdon-tube-type gages. These gages were calibrated against a Heise gage by pressurizing the system statically to various levels. Statham differential pressure transducers were used to measure test-section and exit-filter pressure drop. A Barton differential pressure gage paralleled the test section transducer. Transducer signals were read on a digital voltmeter. Fuel pressures were established by nitrogen pressurization of the waste fuel tank. The supply tank pressure was set slightly higher than that of the waste tank, and flow rate was controlled by a combination of throttling and pressure difference.

## Data

Measurements were taken at 15- or 30-minute intervals, and critical parameters were plotted as a function of time. The parameters considered were exit fuel temperature, wall temperatures, flow rate, fuel pressure, electrical power, and pressure drops across test section and exit filter.

Tube wall temperatures were plotted as a function of length at various times during each run. The variation in wall temperature with time was then studied for evidence of a deterioration in heat-transfer coefficient because of deposits.

The tubes were cut into lengths and analyzed for carbon accumulation by a combustion technique. This procedure is described in the appendix. The total carbon weight measured for each length was then converted into various units including local average carbon deposit per unit surface area. A total integrated carbon accumulation for each test was calculated by assuming a linear variation between measurements. This combustion method provided a very sensitive quantitative measure of the accumulation of carbon, the predominant element in the fuel deposits.

## RESULTS

### Effect of Oxygen Content and Pressure on Local Deposit

The principal quantitative measurements made were the amount of carbon (a measure of deposits) and its distribution along the length of the heated tubes. Carbon was directly measured as a function of position along the tube; these deposits varied with pressure, oxygen content, and fuel. The same amount of fuel (60 lb or 27.2 kg) was used in all tests so the results could be directly compared.

The most thermally stable fuel investigated was LeRC 67-1. This fuel was run deoxygenated at 2.5, 20, 165, and 315 psia ( $1.72 \times 10^4$ ,  $13.75 \times 10^4$ ,  $113.5 \times 10^4$ , and  $217 \times 10^4$  N/m<sup>2</sup> abs) and air-saturated at 165 and 315 psia ( $113.5 \times 10^4$  and  $217 \times 10^4$  N/m<sup>2</sup> abs). The distribution of carbon along the tubes run with this fuel is shown in figure 2(a) where carbon deposits per unit area are plotted against tube length. In all six runs there was a clearly defined maximum of the adhering deposits in one portion of the tube. These maximums were not on the hottest surface (tube outlet) but formed at varying distances upstream of the tube outlet.

The degrading effect of dissolved oxygen is very clearly shown at both 165 and 315 psia ( $113.5 \times 10^4$  and  $217 \times 10^4$  N/m<sup>2</sup> abs) where the air-saturated fuel (solid lines in fig. 2(a)) laid down from 3 to 10 times more deposits in the region of maximum buildup than did the deoxygenated fuel (dashed lines).

With deoxygenated fuel, increasing the pressure from 2.5 to 20 psia ( $1.72 \times 10^4$  to  $13.75 \times 10^4$  N/m<sup>2</sup> abs) resulted in increased deposits. However, further increases in pressure to 165 and 315 psia ( $113.5 \times 10^4$  and  $217 \times 10^4$  N/m<sup>2</sup> abs) very greatly reduced the amounts of deposits to a level well below that obtained at 2.5 psia ( $1.72 \times 10^4$  N/m<sup>2</sup> abs). An opposite effect of pressure was noted with the air-saturated fuels. About twice the peak deposits were observed at 315 psia ( $217 \times 10^4$  N/m<sup>2</sup> abs) than at 165 psia ( $113.5 \times 10^4$  N/m<sup>2</sup> abs).

The results from tests on the somewhat less stable fuel LeRC 67-2 are shown in figure 2(b) for runs at 165, 315, and 615 psia ( $113.5 \times 10^4$ ,  $217 \times 10^4$ , and  $424 \times 10^4$  N/m<sup>2</sup> abs), respectively. This fuel was not run at 2.5 and 20 psia ( $1.72 \times 10^4$  and  $13.75 \times 10^4$  N/m<sup>2</sup> abs) since there is little practical interest in systems running at such pressures, and particularly since no advantage was noted for low pressures with LeRC 67-1. Instead, runs were made at 615 psia ( $424 \times 10^4$  N/m<sup>2</sup> abs) which more nearly corresponds with current practice; it is also a pressure that is greater than the critical pressure of the fuel ( $\approx 315$  psia or  $217 \times 10^4$  N/m<sup>2</sup> abs). It can be seen that the general level of deposits was higher with LeRC 67-2 than with LeRC 67-1 for all tests made under the same conditions.

Again the degrading effect of oxygen is clearly evident. At 315 psia ( $217 \times 10^4$  N/m<sup>2</sup>

abs) the deposit peaks were about 10 times higher with the air-saturated fuel. The effect of pressure was less marked with deoxygenated fuel. With air-saturated fuel, the maximum deposits were much greater at the intermediate pressure of 315 psia ( $217 \times 10^4$  N/m<sup>2</sup> abs).

The results obtained with LeRC 67-2 differed from LeRC 67-1 in that the air-saturated runs at 165 and 315 psia ( $113.5 \times 10^4$  and  $217 \times 10^4$  N/m<sup>2</sup> abs) gave two maximums instead of one in the plots of deposits as a function of tube length. One was at about 28 inches (0.71 m) from the inlet and the second near the tube outlet. However, only one peak was observed at 615 psia ( $424 \times 10^4$  N/m<sup>2</sup> abs).

Data for the third fuel, RAF 178-64, are plotted in figure 2(c). This fuel was run both air-saturated and deoxygenated at 165, 315, and 615 psia ( $113.5 \times 10^4$ ,  $217 \times 10^4$ , and  $424 \times 10^4$  N/m<sup>2</sup> abs).

The degrading effect of oxygen is again clearly shown, and there are two maximums for the air-saturated fuel at all pressures. The first maximum disappeared in all cases when the fuel was deoxygenated. The second maximum near the tube outlet was substantially the same for both the air-saturated and deoxygenated conditions.

This fuel was clearly poorer in the deoxygenated state than the other two in that more deposits were formed. This was especially true at 165 psia ( $113.5 \times 10^4$  N/m<sup>2</sup> abs). In the air-saturated state the maximum deposits were less than those obtained with LeRC 67-2 fuel and little different from LeRC 67-1 levels. The deposit level decreased with increasing pressure with both deoxygenated and air-saturated fuel.

## Effect of Oxygen Concentration and Pressure on Total Deposits

The data presented in figure 2 were integrated along the lengths of the tubes to obtain the total deposits shown in figure 3. These totals are plotted as a function of pressure for the three fuels and two oxygen contents investigated.

There were eight pairs of runs where the oxygen content was the only variable, and in all cases, the air-saturated fuel resulted in greater total deposits than the corresponding deoxygenated run. Oxygen increased the amounts of deposits from about threefold to over tenfold.

The effect of varying pressure on total deposits is less distinct. When deoxygenated, fuels LeRC 67-1 and RAF 178-64 gave decreasing deposits with increasing pressure, but LeRC 67-2 showed the opposite trend. When air-saturated, LeRC 67-2 showed first increasing and then decreasing deposits, and RAF 178-64 gave continuously decreasing deposits with increasing pressure.

Fuel LeRC 67-1 was clearly the best of the three fuels at conditions where all three were tested (165 and 315 psia or  $113.5 \times 10^4$  and  $217 \times 10^4$  N/m<sup>2</sup> abs). Only LeRC 67-1

was run at 2.5 and 20 psia ( $1.72 \times 10^4$  and  $13.75 \times 10^4$  N/m<sup>2</sup> abs) and only this same fuel was not run at 615 psia ( $424 \times 10^4$  N/m<sup>2</sup> abs).

## Deposits and Tube Wall Temperatures

Fluid temperatures were measured only at the tube inlet and outlet where they were 70° and 700° F (294 and 644 K) in all runs. Tube wall temperatures were determined at five to eight stations to allow estimates of the wall temperatures at the places where carbon deposits were measured. Plots on semilog paper of carbon deposits as a function of tube wall temperature are given in figures 4(a) to (c) for fuels LeRC 67-1, LeRC 67-2, and RAF 178-64, respectively. These figures can be used to determine the approximate metal temperature at which deposits first become significant and the temperature corresponding to deposit peaks.

The selection of an incipient deposit formation level (prior to a rapid deposit increase) must be somewhat arbitrary. On the basis that the combustion techniques for determining the deposits (carbon) were sensitive to about  $0.02 \times 10^{-6}$  pound of carbon per square inch ( $1.43 \times 10^{-6}$  g/cm<sup>2</sup>) of surface area, a value 10 times larger ( $0.2 \times 10^{-6}$  lb/in.<sup>2</sup> or  $14.3 \times 10^{-6}$  g/cm<sup>2</sup>) was selected as the incipient deposit level for the wall temperatures listed in the following table:

Fuel	Pressure		Deoxygenated		Air-saturated	
	psia	N/m <sup>2</sup> abs	Wall temperature for incipient deposits			
			<sup>o</sup> F	K	<sup>o</sup> F	K
LeRC 67-1	2.5	1.72×10 <sup>4</sup>	365	460	---	---
	20	13.75	495	530	---	---
	165	113.5	605	595	385	470
	315	217	705	650	460	510
LeRC 67-2	165	113.5×10 <sup>4</sup>	590	585	330	440
	315	217	595	590	410	485
	615	424	570	575	380	465
RAF 178-64	165	113.5×10 <sup>4</sup>	615	600	320	435
	315	217	625	605	330	440
	615	424	670	630	310	430

This table clearly shows the adverse effect of the presence of dissolved oxygen. The metal temperatures for incipient deposit formation are from 185<sup>o</sup> to 360<sup>o</sup> F (103 to 200 K) lower when the fuels were saturated with air as compared with the corresponding runs with deoxygenated fuel.

Increasing the pressure increased the wall temperature for incipient deposits with fuel LeRC 67-1. This appears to be true for both the deoxygenated and air-saturated fuel. Pressure had a less consistent effect on the other two fuels. Fuel LeRC 67-1 was clearly better than the other two in that it had a higher wall temperature.

The wall temperatures for the first peak in carbon deposit taken from figure 4 are listed in the following table:

Fuel	Pressure		Deoxygenated		Air-saturated	
	psia	N/m <sup>2</sup> abs	Wall temperature for incipient deposits			
			°F	K	°F	K
LeRC 67-1	2.5	1.72×10 <sup>4</sup>	470	520	---	---
	20	13.75	535	555	---	---
	165	113.5	680	635	640	610
	315	217	740	670	575	575
LeRC 67-2	165	113.5×10 <sup>4</sup>	615	600	550	560
	315	217	700	645	530	550
	615	424	710	650	550	560
RAF 178-64	165	113.5×10 <sup>4</sup>	710	650	520	545
	315	217	740	670	480	525
	615	424	830	720	450	510

Again, the adverse effect of dissolved oxygen is clear. When the fuel was deoxygenated, increasing the pressure always increased the wall temperature at which the peak deposit was formed. The effect of pressure was less pronounced when the fuels were saturated with air. It may be noted from figure 2 that when there were two significant maximums associated with the air-saturated tests, the second peak occurred at nearly the same location as the single peak with deoxygenated fuel.

### Comparison with Coker Tests

Standard coker tests were run on RAF 178-64 and modified coker tests were run on LeRC 67-1 at progressively higher temperatures until the fuels failed the visual rating

for deposits on the preheaters. The coker tests were performed on air-saturated fuel at 165 psia ( $113.5 \times 10^4 \text{ N/m}^2 \text{ abs}$ ). The preheater fuel outlet temperatures at which failure occurred, based on code 3 visual rating (table I), were  $300^\circ \text{ F}$  ( $422 \text{ K}$ ) for RAF 178-64 in the standard coker and  $450^\circ \text{ F}$  ( $505 \text{ K}$ ) for LeRC 67-1 in the modified coker. These are fuel-out temperatures but the corresponding maximum preheater surface temperatures can be taken from curves given in reference 9. These surface temperatures are  $420^\circ \text{ F}$  ( $489 \text{ K}$ ) for RAF 178-64 and  $520^\circ \text{ F}$  ( $544 \text{ K}$ ) for LeRC 67-1. These values can be compared with the temperatures of  $320^\circ \text{ F}$  ( $433 \text{ K}$ ) for RAF 178-64 and  $385^\circ \text{ F}$  ( $468 \text{ K}$ ) for LeRC 67-1 listed previously as the temperatures for incipient deposit formation with air-saturated fuels run at 165 psia ( $113.5 \times 10^4 \text{ N/m}^2 \text{ abs}$ ).

Clearly, the surface temperatures listed herein as those for incipient deposit formation are considerably lower than those found in the fuel coker tests. Three factors may be responsible. First, more fuel was used per unit surface area in the present work. Second, the criterion of  $0.2 \times 10^{-6}$  pound of carbon per square inch ( $14.3 \times 10^{-6} \text{ g/cm}^2$ ) used herein may represent a thinner deposit than a code 3 visual rating. And finally, the Nichrome V tubing may have a mild catalytic effect as compared with the aluminum tubing used in the standard test.

## Other Observations

Some data other than the amounts of carbon along the tubes were obtained during these tests. These include the effects of deposits on tube wall temperatures and pressure drops and some observations on the solids entrained in the flow stream.

The variation in wall temperature with time was generally greatest in the same general areas where the peak deposits were later measured. Since from five to eight thermocouples were equally spaced along the length, these thermocouple positions did not necessarily correspond to the locations where maximum deposits were determined. In runs where a thermocouple was located close to the peak deposits, a definite increase in wall temperature or decrease in heat-transfer coefficient was evident. However, the data were not adequate for a quantitative estimate of the decreases in heat-transfer coefficient.

No significant change in pressure drop was measured except for run 14 where it increased about 10 percent during the test. This run also had the highest local carbon deposits ( $19.9 \times 10^{-6} \text{ lb/in.}^2$  or  $14.0 \times 10^{-6} \text{ g/cm}^2$ ). If this deposit is assumed to have a specific gravity of 1.0 and to be two-thirds carbon, the deposit thickness would be 0.00083 inch (0.00211 cm). This is slightly less than a 1 percent reduction in area for a 0.116-inch- (0.295-cm-) inside-diameter tube and would not account for a 10 percent increase in pressure drop. However, the deposit may be porous and have a specific

gravity much less than 1. Also, the  $19.9 \times 10^{-6}$ -pound-per-square-inch ( $14.0 \times 10^{-6}$ -g/cm<sup>2</sup>) amount is an integrated value over a 2-inch (5.1-cm) length of tube, and deposits might have been thicker locally.

All the deposits were too thin to change the appearance when sighting down the tube. However, the walls of the exit plenum and its two thermocouples were blackened in every test. These deposits were thin and not easily wiped off. They shorted the bare bead thermocouples during some tests, but only one test had to be interrupted when both thermocouples became erratic. The sintered metal filters used in the first five tests are shown in figure 5. The filters were blackened, but the coating was not thick enough to change their surface texture. No attempt was made to rate these deposits.

The fuel drained from the waste fuel tank was found to be yellowed and have a strong odor. No change in specific gravity was noted.

## DISCUSSION

The carbon deposition data presented in figures 2 to 4 along with other observations are only semiquantitative in that no runs were repeated. Therefore, the repeatability and accuracy of all this work is not proven. Nevertheless, there are definite trends regarding the effects of temperature, pressure, and dissolved oxygen on the deposition of solids in heated tubes.

Even though the data are not rigorously quantitative, there are conclusions that can be drawn regarding the mechanisms of solid deposition and the possibility of heating fuels to 700° F (644 K) in aircraft fuel systems. The following is a discussion of these aspects.

### Mechanism

Two types of deposit-forming reactions are indicated. The RESULTS section and related figures show that deposits were formed at lower temperatures and much closer to the tube inlet when the fuels contain dissolved oxygen. Often there are two maximums in the plots of deposit weight against tube length (or temperature), one at relatively lower temperatures and the other near the hotter tube outlet. The first maximum disappeared when the dissolved oxygen was removed while the second was generally only slightly influenced by oxygen content.

In summary, there appear to be two deposit-forming processes. The one occurring first in the tube or at a lower tube wall temperature requires the presence of oxygen and is therefore considered to be primarily an oxidation process, although there is a thermal



requirement for reaction of impurities with oxygen. This process is considered to be analogous to that occurring in standard coker tests wherein the fuel is aerated before testing. The second peak appears at generally the same location and wall temperature for a given pressure with or without oxygen and is therefore considered to be primarily a thermal process.

## Composition and Amounts of Deposits

The deposits formed from thermally unstable fuels are believed to be derived largely from traces of nonhydrocarbon impurities in the fuels. These are sulfur-, oxygen-, and nitrogen-containing organic compounds. These impurities, along with the more reactive hydrocarbons and dissolved oxygen, condense and polymerize to form high-molecular-weight materials that are insoluble in fuel. Some of these deposits are on the tube wall, and some are suspended in the fuel and may foul downstream fuel-system components.

Although the precise chemical composition is not known, attempts to analyze the deposits and a knowledge of the materials involved permit a deduction of the approximate composition. The insolubility of the material to all organic solvents indicates that it is not a hydrocarbon polymer, such as polyethylene or polystyrene. The influence on thermal stability of dissolved oxygen and nonhydrocarbon fuel impurities suggests that the deposit contains carbon, hydrogen, oxygen, and nitrogen. Sulfur may also be present. Industrial polymers that contain these elements and which also have similar resistance to organic solvents are, as examples, the alkyd and epoxy resins and nylon. Typical members of these three classes of polymers have carbon contents of 63, 76, and 63 percent, respectively, and specific gravities ranging from 1.0 to 1.3. For purposes of discussion herein, the deposits were assumed to be 67 percent carbon and to have a specific gravity of 1.0. However, there have been unpublished indications that the deposit consistency could have a porous "popcorn" character and have a lower specific gravity. Thermal conductivity values in the neighborhood of 0.07 Btu per hour per square foot per °F per foot (0.121 J/(m)(sec)(K)) are recommended in reference 10 based on similar logic.

The amounts of deposits formed were very small in all tests. Integration of the plots shown in figure 2 gave the totals shown in figure 3. The values of accumulated carbon deposits in figure 3 range from  $2 \times 10^{-6}$  to  $100 \times 10^{-6}$  pounds ( $908 \times 10^{-6}$  to  $45\,400 \times 10^{-6}$  g) of carbon. Since 60 pounds (27.3 kg) of fuel were used during each test and the carbon fraction of the deposit was chosen as 0.67, the deposits range from 0.05 to 2.5 ppm of the fuel.

## Effects of Deposits on Engine Performance

The possibility of heating fuels to 700<sup>0</sup> F (644 K) can be considered from various standpoints, that is, weight of deposit accumulation in aircraft heat exchangers, potential flow blockage problems, and degradation of heat-transfer rate. The discussion that follows is quantitatively only as valid as the assumptions made relative to deposit carbon content, specific gravity, and thermal conductivity. In addition, it is assumed that the deposits increase linearly with accumulated flow or time; for example, that there would be 10 times more deposits with 600 pounds (273 kg) of fuel than there were in these tests with 60 pounds (27.3 kg) of fuel.

An SST uses about 200 000 pounds of fuel (90 800 kg) during a typical flight. The potential weight accumulation is obtained by multiplying this fuel weight by the fraction of deposit formed from the fuel. This fraction ranged from 0.05 to 2.5 ppm, indicating a potential deposit weight accumulation per flight of from 0.01 to 0.5 pound (4.54 to 228 g) in engine fuel heat exchangers.

The carbon distribution curves presented herein indicate that local deposit formation may present a more significant problem than total weight accumulation. Considering the tube blockage problem, the estimated times to block the flow area of a 0.116-inch- (0.295-cm-) diameter passage by 50 percent are tabulated below. The two carbon growth rates represent the smallest and largest local peak values obtained during these tests.

Source of local growth rate	Carbon growth rate		Time for 50 percent blockage, hr
	lb/in. <sup>2</sup> per 20 hr	g/cm <sup>2</sup> per 20 hr	
Maximum (air-saturated tests)	19.9×10 <sup>-6</sup>	14.0×10 <sup>-6</sup>	400
Minimum (min. oxygen tests)	.5	.36	16 000

These figures provide an indication of the time involved if it is assumed that the deposits have a specific gravity of 1.0 and contain 67 percent carbon. A mean surface area was assumed in the calculation. These estimates assume a linear growth rate from the 20-hour run time and imply that the maximum rates of deposition will remain at one tube location. In practice there will be time-varying flow rates, wall temperatures, and heat-transfer coefficients that will tend to spread the deposit over a considerable length.

The degradation of heat exchanger performance due to scale formation (deposits) is thoroughly treated in the literature. The deposit forms an insulating blanket which can become the dominant factor controlling heat flux. In a fuel-to-air heat exchanger this insulating blanket can seriously alter the heat balance considered in design, that is, the air would be cooled less and the fuel heated less. Obviously, if this occurs the heat sink capacity of the cooling air for turbine cooling would decrease with time and either the engine would have to be progressively derated or failure could be expected.

As the deposits only affect the fuel side of a fuel-to-air heat exchanger, the influence of deposits on fuel-side design heat flux or, as the temperatures can be assumed to be constant, at various design heat-transfer coefficients can be discussed. During the tests reported herein, a typical heat-transfer coefficient  $h$  was 58 Btu per hour per square foot per  $^{\circ}\text{F}$  ( $32.9 \text{ W}/(\text{m}^2)(\text{K})$ ) between the surface and the fuel. The following relation provides a heat-transfer coefficient from wall to fluid  $u$  with a conduction term for scale or deposit effects:

$$\frac{1}{u} = \frac{1}{h} + \frac{x}{K}$$

where

$x$  deposit thickness

$K$  thermal conductivity of deposit

Figure 6(a) illustrates the decrease with time of the local heat-transfer coefficient from a design value due to each of three possible deposit growth rates. A  $K$  value of 0.07 Btu per hour per square foot per  $^{\circ}\text{F}$  per foot ( $0.121 \text{ J}/(\text{m})(\text{sec})(\text{K})$ ) is assumed. The design or clean-tube value of  $u$  is 58 Btu per hour per square foot per  $^{\circ}\text{F}$  ( $32.9 \text{ W}/(\text{m}^2)(\text{K})$ ). The three carbon deposit rates (for 20 hours) plotted are  $0.2 \times 10^{-6}$ ,  $4.3 \times 10^{-6}$ , and  $1420 \times 10^{-6} \text{ g}/\text{cm}^2$ . These values correspond to the previously discussed incipient deposit formation rate and the maximum rates found with deoxygenated and with air-saturated fuels in tests above 300 psia ( $207 \times 10^4 \text{ N}/\text{m}^2 \text{ abs}$ ). The decay curve for air-saturated fuel indicates that the heat-transfer coefficient decays to 50 percent of design value in 350 hours. The decay curve for deoxygenated fuel indicates that 1600 hours are required to diminish the design  $u$  by 50 percent. The decay curve associated with the  $0.2 \times 10^{-6}$ -pound-per-square-inch ( $14.3 \times 10^{-6} \text{ g}/\text{cm}^2$ ) carbon deposit rate shows only a 15 percent reduction in 6000 hours. Deposit growth rate could be limited to the inception growth rate with a sacrifice in heat sink capacity by utilizing deoxygenated fuel and limiting the wall temperature to around  $570^{\circ} \text{ F}$  ( $573 \text{ K}$ ).

Figure 6(b) is included to illustrate that if a heat exchanger is designed for a higher heat flux (higher heat-transfer coefficient assuming the same wall- to fluid-temperature

difference), the deposit growth rate has a more significant effect on heat exchanger performance. In this figure the design heat-transfer coefficient is increased by a factor of ten from figure 6(a), and the same deposit growth rates are assumed to be valid. As may be noted, the time for decay to 50 percent of design  $u$  is reduced to 160 hours for deoxygenated fuel and 3400 hours at the inception deposit rate.

Figure 6 tends to verify previous pessimism concerning the further utilization of the heat sink of existing commercial fuels if the fuel is air-saturated. The figure also indicates the potential for significant gains if deoxygenated fuel is used and heating occurs when the fuel is at a desirable pressure. This figure also illustrates the desirability of designing for low liquid-side heat flux to reduce the influence of the deposits. Unfortunately, this leads to undesirably large heat exchangers. Reduction in local heat-transfer coefficient due to deposit formation is a more significant or limiting problem than either weight accumulation or blockage.

Although this effort was not intended as a fuels test, the fuels do represent a significant range within the ASTM Jet A specifications. If specifications were tightened and handling procedures were improved to the point that the LeRC 67-1 fuel was the poorest to design for from a stability standpoint, fuel-to-air heat exchanger time between overhauls in excess of 3000 hours could be readily expected.

Another approach suggested by this work would be to design the heat exchanger so that segments of the fuel side would be shut off, and air introduced periodically. With approximately 1200° F (923 K) compressor bleed air on both the liquid side and the air side, a combustion process would remove the accumulated deposits in much the same way as described in the appendix. Perhaps a more immediately practical consideration would be to have the heat exchanger removed during overhaul and cleaned in an oven with airflow on the fuel side.

## CONCLUDING REMARKS

Only small amounts of deposits were collected on heat exchanger surfaces when Jet A fuels were heated to 700° F (644 K) at a nominal heat flux of 9000 Btu per hour per square foot (2830 W/m<sup>2</sup>). The accumulated deposits ranged from 0.05 to 2.5 parts per million of the fuel so heated. The deposits were always reduced by removing dissolved oxygen from the fuel prior to heating.

The influence of fuel pressure, while not entirely consistent from fuel to fuel, was to diminish both total and local deposits with increasing pressure. Increasing fuel pressure also shifted peak deposit locations downstream to points corresponding to higher wall temperatures.

Times between overhauls for an SST would be uneconomically short due to deposits

if air-saturated fuels were heated to 700<sup>0</sup> F (644 K) under the heat-transfer conditions of these experiments. However, the rates of deposition with fuels containing minimum oxygen were not so high as to deny the possibility of heating fuels to 700<sup>0</sup> F (644 K) in advanced aircraft engines. It is, therefore, possible that adequate times between overhauls can be achieved if high-quality fuels meeting the Jet A specification are deoxygenated and used in conservatively designed heat exchangers. The possibility of heating fuels to 700<sup>0</sup> F (644 K) prior to burning provides considerably greater heat sink capacity for cooling of engine components than is currently available.

It is postulated that there are two mechanisms involved in heat exchanger fouling when fuels are strongly heated. One is an oxidative degradation that takes place in the liquid phase and is probably identical with the thermal instability process that has received much attention in recent years. The other is a higher-temperature process that is much less influenced by dissolved oxygen. Two peaks in deposit formation representing the two mechanisms occurred frequently during tests with air-saturated fuel. The first peak corresponding to a lower wall temperature disappeared when the fuel was tested with minimum oxygen.

Finally, a combustion technique has been shown to be capable of quantitatively measuring the carbon weight distribution in the passages. The technique is quick, easy, and accurate. The carbon measurements are not directly applicable to design as neither the exact percentage of carbon in the fuel deposits nor the deposit specific gravities are known. Nevertheless, the data do show the trends that result from changes in operating variables. The combustion technique may prove valuable in fuel evaluation and provide a method for cleaning fuel-to-air heat exchangers fouled by fuel deposits.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, September 23, 1968,  
126-15-01-38-22.

## APPENDIX - DETERMINATION OF CARBONACEOUS DEPOSITS

Sample tubes from the fuel deposit experiments were first rinsed by passing a volatile solvent, such as hexane, through the tube to remove any remaining fuel and then dried with air. The outside of each tube was cleaned with abrasive paper or steel wool to remove any organic matter that might have been left on the tube. Several 2-inch (5.08-cm) sections, spaced approximately 10 inches (25.4 cm) apart, were then cut from each tube. Additional 2-inch (5.08-cm) sections were cut later, as required, both before and after the section showing the largest amount of deposit, in order to more accurately define the deposit distribution. In this way, six to ten sections were taken from each tube. Each test section was carefully cleaned with lintless tissue and ether to remove fingerprints, etc., and thereafter was handled with clean tweezers.

The apparatus used to determine residual carbonaceous deposits was an adaptation of a Leco Low Carbon Analyzer (Laboratory Equipment Corp., St. Joseph, Mich.). The complete instrument is shown in figure 7(a), and a schematic diagram showing the way it was used to evaluate these samples is shown in figure 7(b). The complete instrument consists of (1) a gas-purifying train, (2) an induction furnace, (3) traps to remove dust and sulfur, (4) a copper oxide furnace to convert carbon monoxide to carbon dioxide, (5) a drying tube filled with magnesium perchlorate, and (6) the analyzer unit. The only modification was to substitute an electric tube furnace for the induction furnace. The furnace tube was made of a high-temperature borosilicate glass 36 inches (91.5 cm) long and 1 inch (2.54 cm) in outside diameter. A sample section was placed in an alundum boat to which was attached a metal rod about 10 inches (25.4 cm) long with a piece of magnetic stainless steel attached to the opposite end. This assembly was held in the unheated part of the furnace tube during purge, then pushed into the furnace section by means of a handheld magnet outside the tube. The deposit was burned off in an oxygen flow of 250 milliliters per minute at a furnace temperature of 520° to 530° C. Eight minutes was sufficient time to completely burn the carbon in the deposits. In the analyzer, carbon dioxide is absorbed in a collector containing about 1 gram of molecular sieve 13X which is at room temperature during the collection part of the cycle. At this point, a timer actuates a solenoid-controlled six-port valve which diverts the oxygen flow to vent and sends helium through the collector. Oxygen is purged from the collector within 10 to 15 seconds. The collector is then heated to 350° C within 20 seconds. At this temperature, carbon dioxide is released by the molecular sieve and carried by the helium through a chromatographic column (a 1/4-inch- (0.03-cm-) o.d. copper tube, 1 ft (30.4 cm) long, packed with silica gel) to a thermal conductivity detector. Output of the detector is amplified and fed to a synchronous motor which drives a clock integrator. Calibration of integrator counts against micrograms of carbon was made by injecting precise amounts of pure carbon dioxide from a gas-tight syringe. The detector has a sensitivity of 0.1 microgram and a range of up to 1000 micrograms of carbon.

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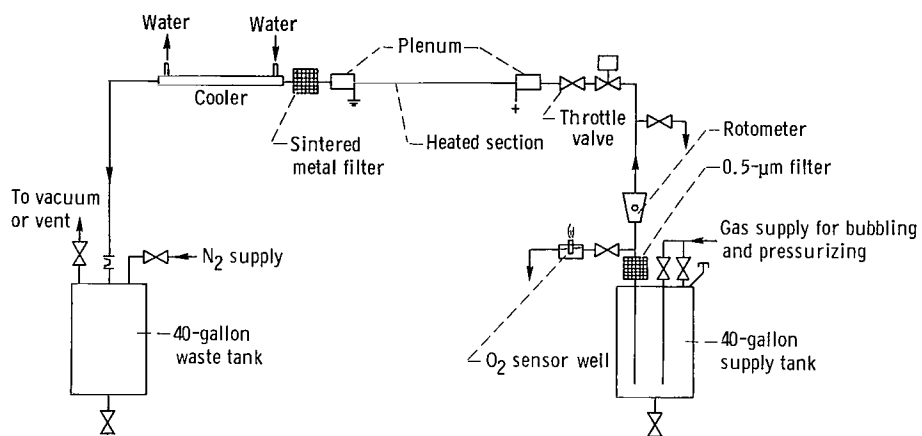


Figure 1. - Schematic of flow system.



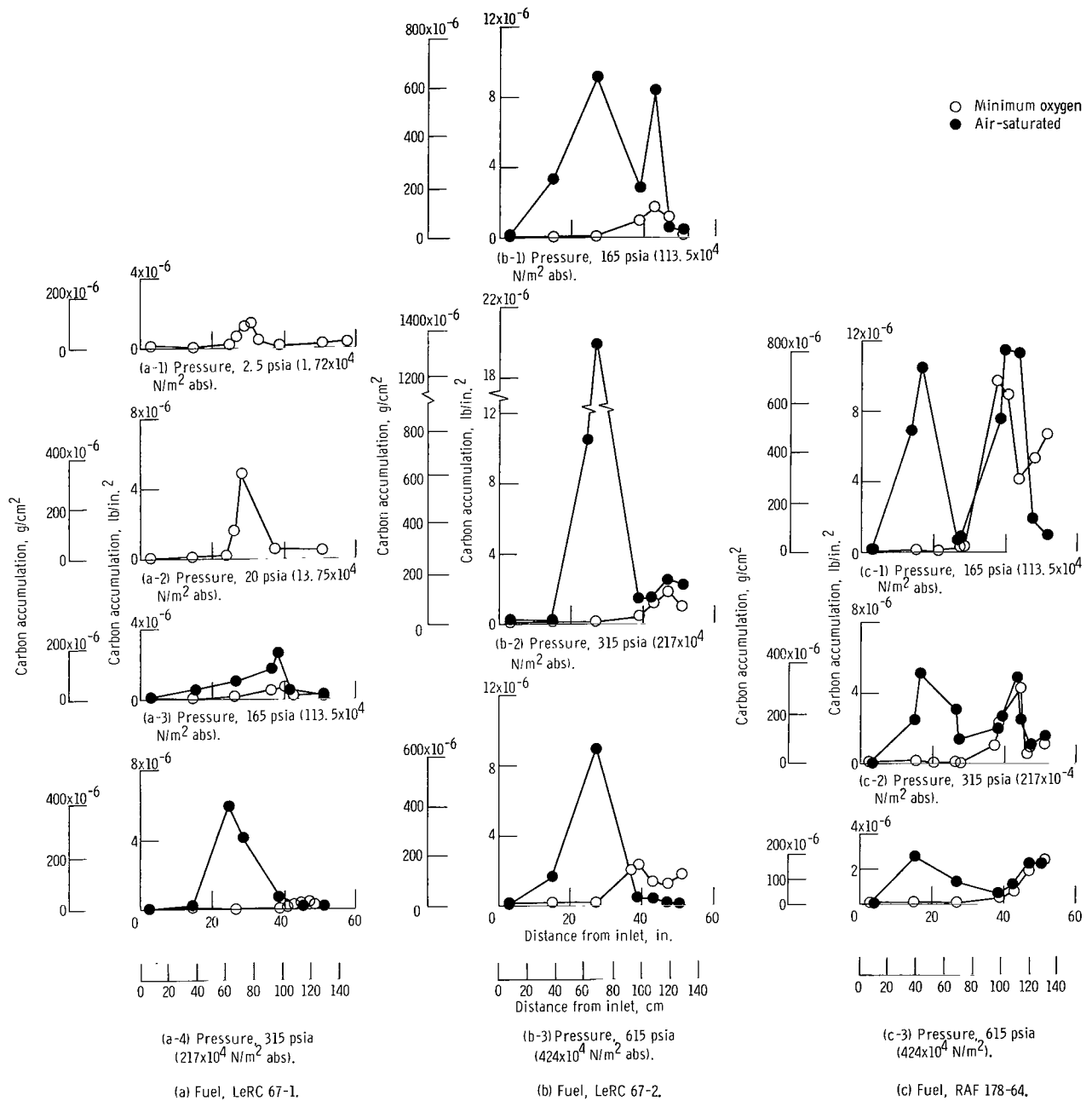


Figure 2. - Carbon weight distribution in tubes tested with three different fuels at various pressures.

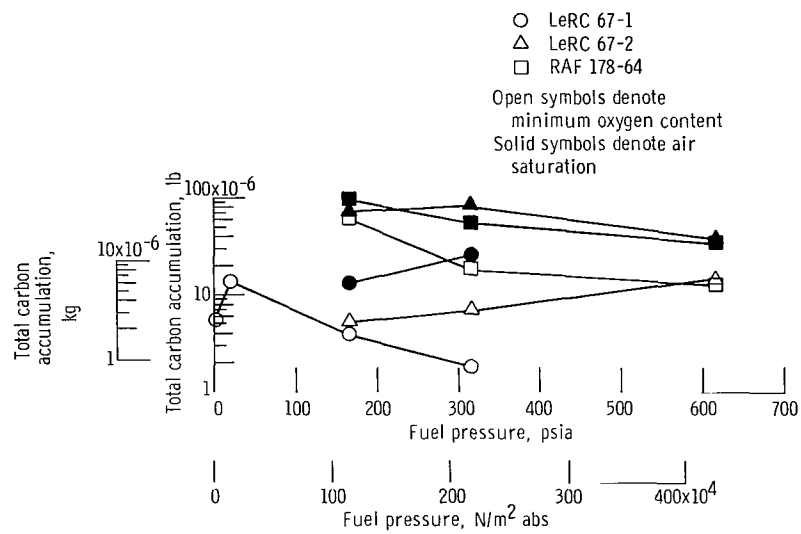


Figure 3. - Influence of fuel oxygen content and pressure level on total carbon accumulation.

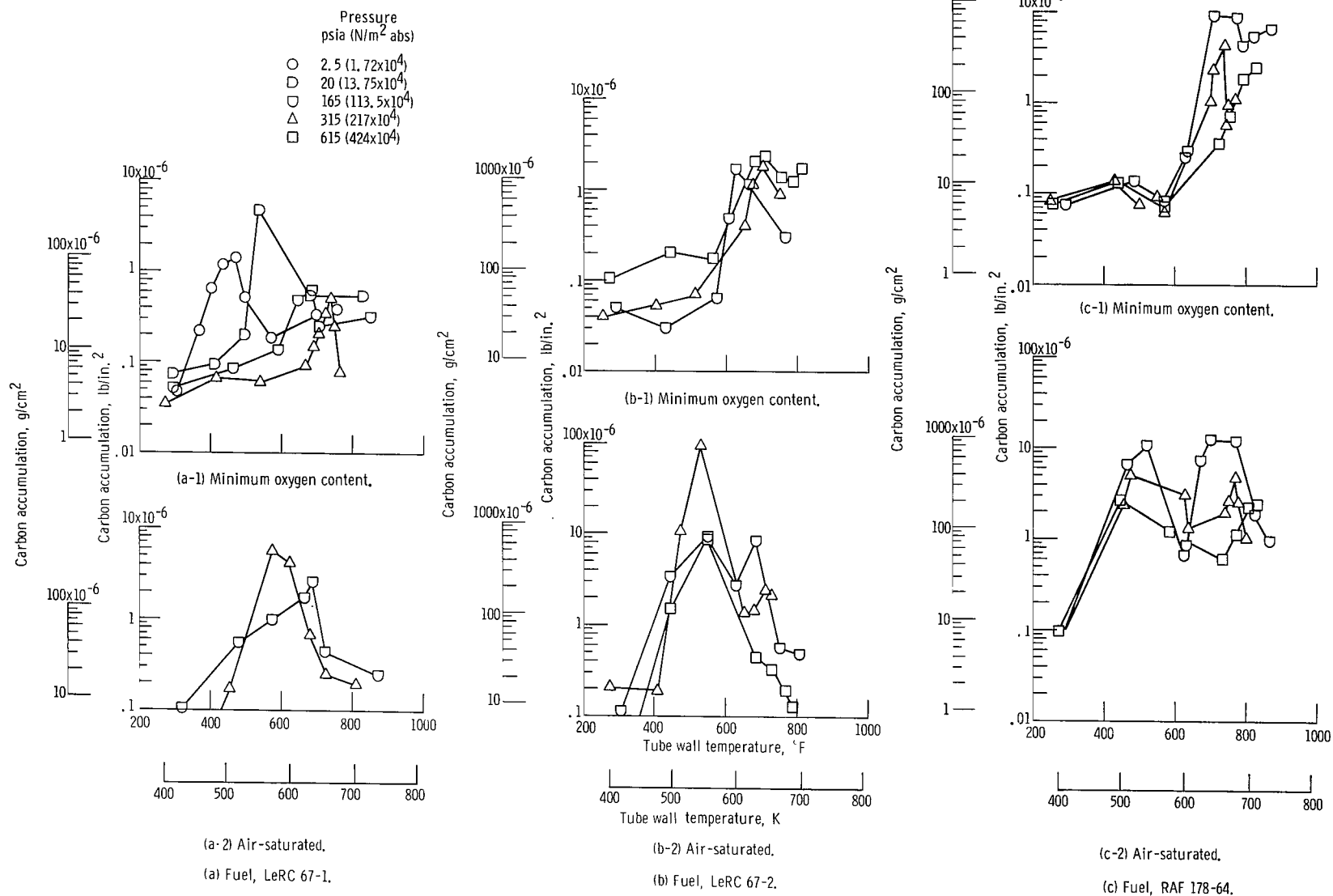


Figure 4. - Carbon weight distribution as function of tube wall temperature.

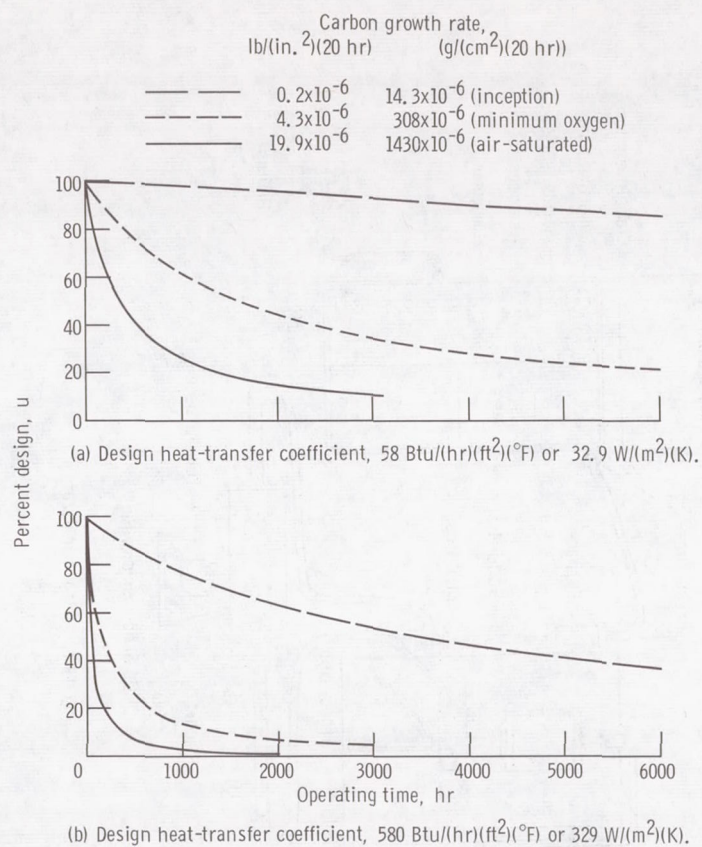


Figure 6. - Decay in local wall-to fluid-heat-transfer coefficient from two design (clean) values due to deposit formation.

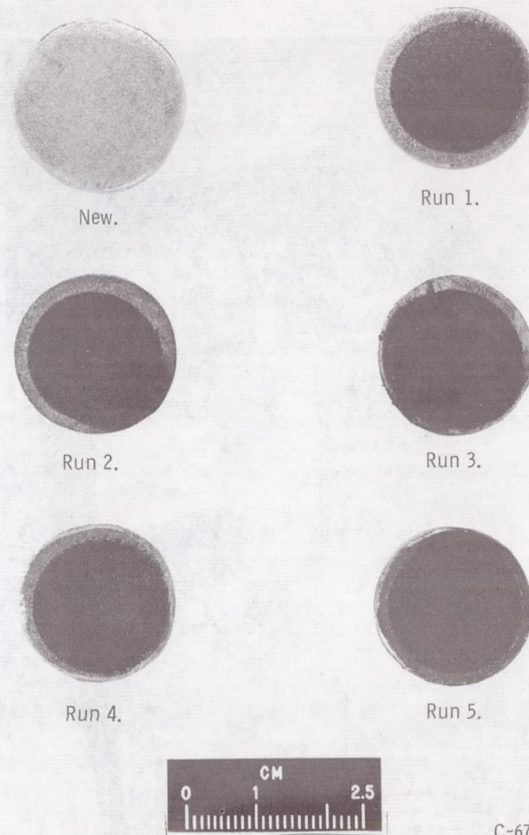
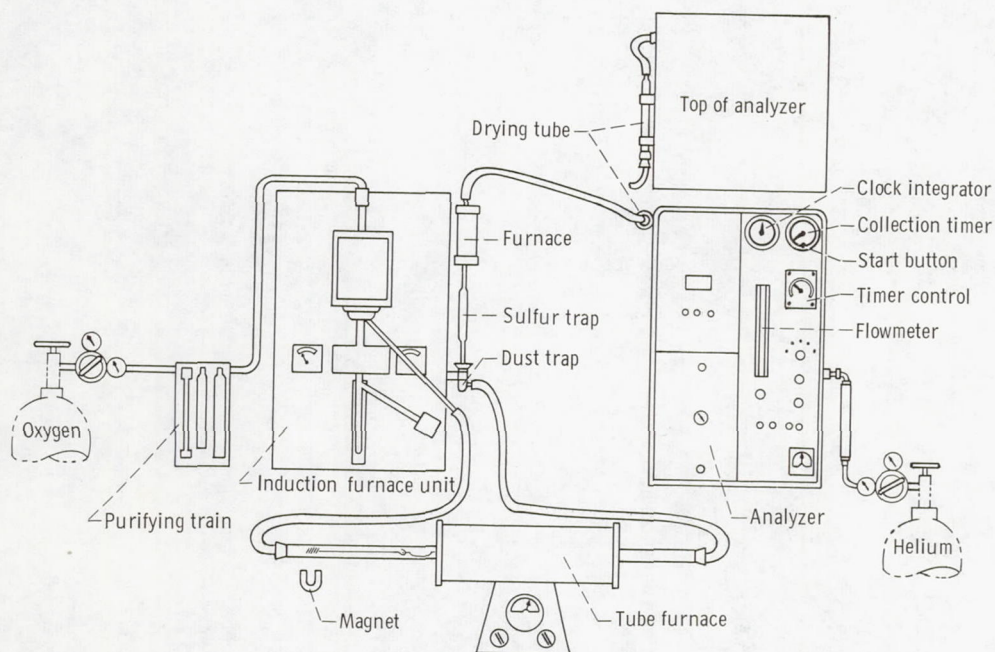
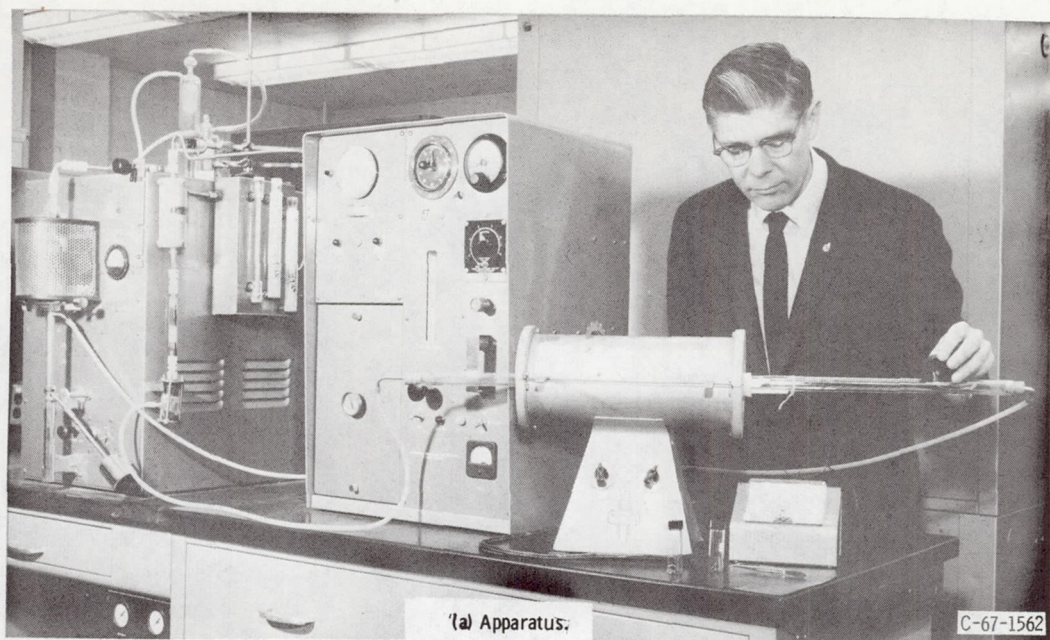


Figure 5. - Sintered metal hot fuel filter.

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(b) Schematic drawing.

Figure 7. - Carbon analyzer.

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